The Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE): a Pathfinder for Next-Generation Extragalactic FIR Spectroscopy

J. E. Aguirre[1], C. M. Bradford[2,3], M. J. Devlin[1], C. Groppi[4], A. Beyer[2], P. D. Mauskopf[4], J. D. Zmuidzinas[2,3], A. C. M. Barlis[1], B. D. Uzgil[1] and S. Hailey-Dunsheath[3]
[1]University of Pennsylvania (209 S. 33rd St, Philadelphia, PA 19104; jaguirre@sas.upenn.edu), [2]Jet Propulsion Laboratory [3]California Institute of Technology [4]Arizona State University

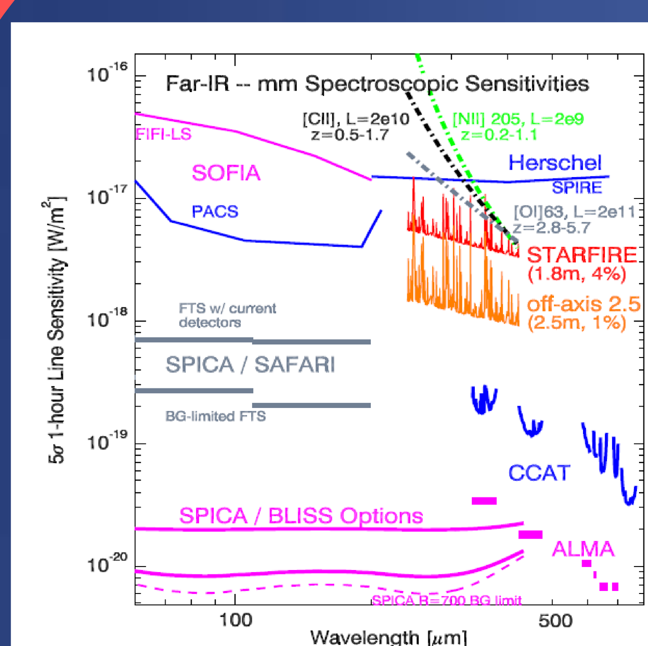
Understanding the formation and evolution of galaxies is one of the foremost goals of astrophysics and cosmology today. The cosmic star formation rate has undergone a dramatic evolution from its peak seven billion years ago, when the bulk of star-forming activity occurred in highly luminous, dust-obscured star forming galaxies (DSFGs), to the present day, when such galaxies are relatively rare. Thus DSFGs offer the perfect tracers of this evolution. By their very nature, DSFGs are difficult to study optically and have, until recently, been poorly understood. A variety of unextincted diagnostic lines are present in the far-infrared (FIR) which can provide redshifts as well as insight into the conditions of star formation, including the instantaneous star formation rate, the effect of AGN feedback on star formation, the mass function of the stars, and the spectrum of their ionizing radiation.

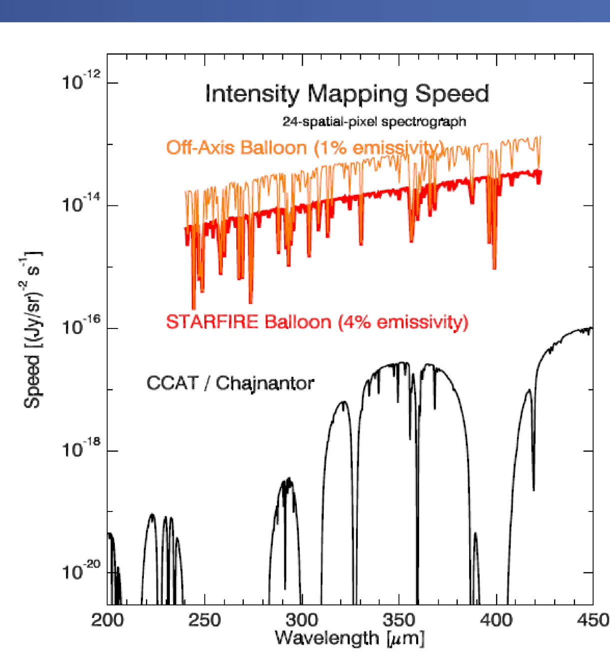
Spectroscopy in the FIR is technically difficult but scientifically crucial to understanding the evolution of galaxies. FIR spectroscopy from a space-based platform with a cryogenic mirror can achieve performance limited by astrophysical backgrounds, but such a platform is expensive, and at present is at least 10 years out (e.g. SPICA now with earliest launch in 2026). We argue that stratospheric balloons offer a platform which can both outperform current capabilities scientifically, and provide a technological stepping stone to the future space-borne instrumentation. This is possible for a telescope using low-emissivity, high-throughput optics onto a dispersive spectrometer, and having high-sensitivity, large-format detector arrays.

Here we describe the Spectroscopic Terahertz Airborne Receiver for Far-InfraRed Exploration (STARFIRE), an aggressive program of instrumentation development and experimental study, with the goal of demonstrating the three key technical milestones necessary for balloon-borne far-infrared spectroscopy limited by the photon noise from the atmosphere: 1) accurate pointing for spectroscopy of point sources, 2) high-throughput spectrometer optics, and 3) background-limited detectors in large format arrays, scalable to >10,000 pixels. We will do this by constructing a dual-band grating spectrometer covering 240 – 420 microns coupled to the proven 1.8 meter BLAST telescope. For the detectors, we will leverage the development work of the Caltech / JPL group to develop and field kinetic-inductance detector (KID) arrays. KIDs represent the most promising route to economical, large format submillimeter detector arrays. In addition to this technical demonstration, we will be able to obtain scientific results from STARFIRE from two North American overnight flights which will obtain spectra of tens of galaxies in the fine structure lines CII(158 micron) (0.5 < z < 1.5), OI(63 micron) and OIII(88 micron) (2 < z < 4).

STARFIRE is explicitly intended as a pathfinder to a more capable Long Duration Balloon (LDB) proposal. Such an experiment would allow a wholly unprecedented experiment to study the cosmic star formation history. This future experiment will make a 3-D cube spanning at once at least 4 billion years of cosmic history (0.5 < z < 1.5), on scales from 1 - 50 Mpc (30" to >1°) with complete spectroscopic information. This would be done with fully three dimensional tomographic maps of emission in [CII] and other lines. Such an experiment fills a unique and vital scientific niche not filled by Herschel, SOFIA, ALMA, or even SPICA as currently conceived. We stress that much of the work for STARFIRE, including the spectrometer optics, detectors, and detector readout, can be directly re-used in a future experiment.

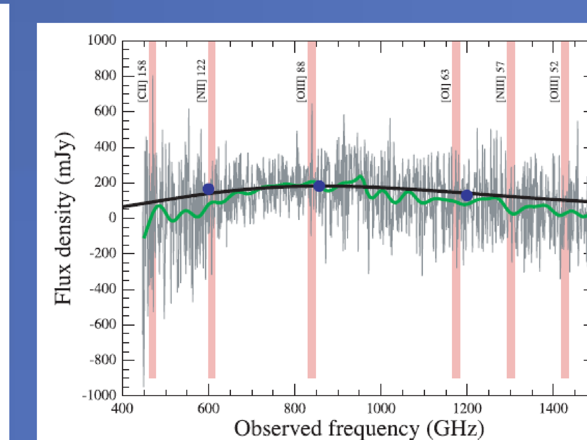
Science

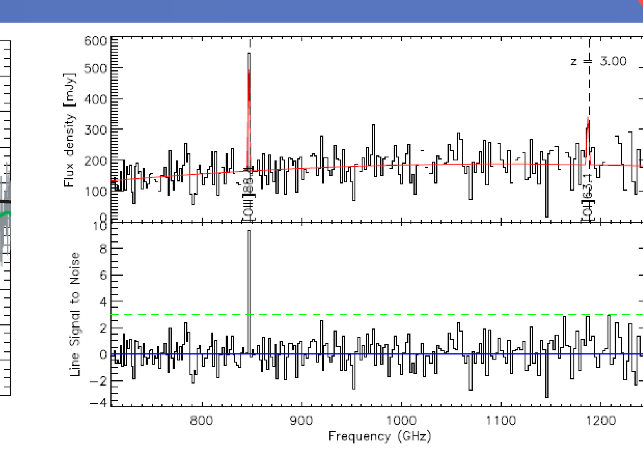




Left: STARFIRE (red) compared to current and future spectroscopic instruments. We compute a 5σ 1-hour sensitivity on a single point source of known redshift as the benchmark. We include a factor of 2 in time as required for chopping between spectral modules. The variation in the STARFIRE sensitivity is due to atmospheric emission lines. Approximately 10% of the band has noise 2× above the median due to these lines; note, though, that these channels are useful for frequency calibration.

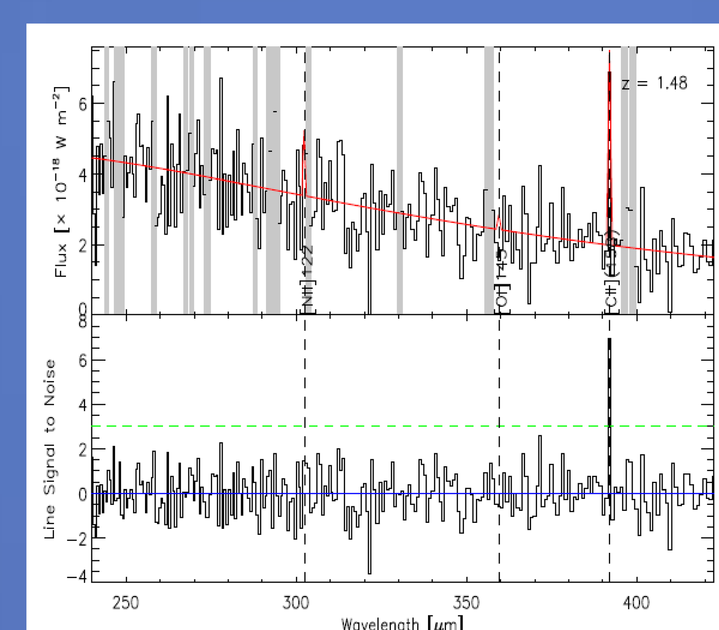
Right: The intensity mapping speed of STARFIRE compared to an identical instrument on CCAT. Here, larger values correspond to more area mapped to the same depth in the same time; a balloon instrument like STARFIRE is as much as 3 orders of magnitude faster. Note that for intensity mapping, telescope area is not a factor. Note also the significant regions in redshift not accessible from the ground even at the best sites. The "off-axis" sensitivities assume a 2.5-meter telescope with an ambitious 1% emissivity, probably the practical limit of individual detector sensitivity achievable from the balloon platform.

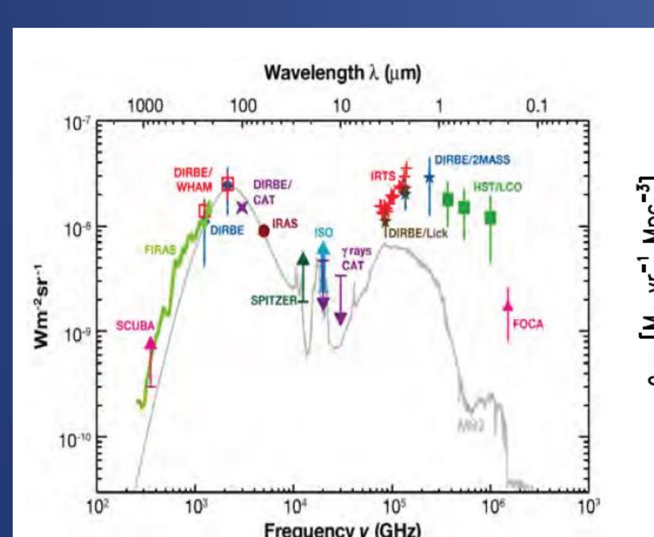


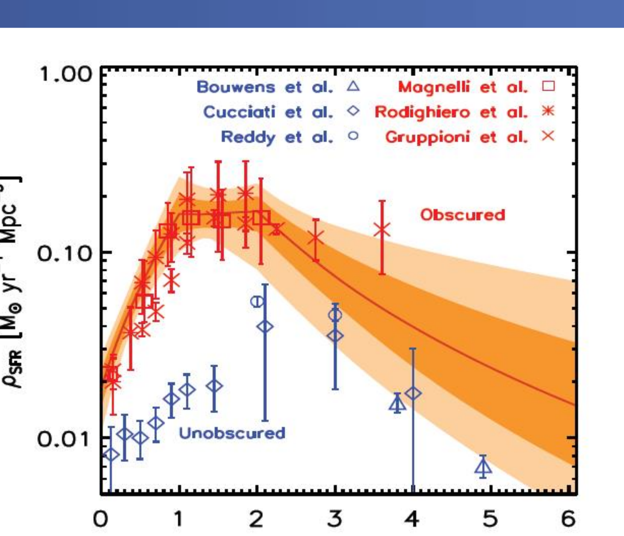


Left: The *Herschel*-SPIRE FTS spectrum of SDP.81 from Valtchanov et al 2011, obtained in ~4 hours. This galaxy was, at the time of publication, the faintest [CII] line yet detected by *Herschel*. *Right:* A the same galaxy observed for 1 hour with STARFIRE, including all overheads. Though [CII] has redshifted out of the STARFIRE band, [OI] 63 µm and [OIII] (88 µm) are clearly detected.

Right: A simulated spectrum of a $L_{FIR} = 2 \times 10^{13}$ galaxy, assuming 1 hour. In addition to [CII] , the continuum is strongly detected (T_{dust} = 35 K is assumed), allowing for pointing and calibration checks. Channels with 2x higher noise than the median are shown in gray (approximately 11% of the total), but the lower panel of the figure shows the SNR accounting for this increased variance, indicating that these channels, while less sensitive, do not create false positives.



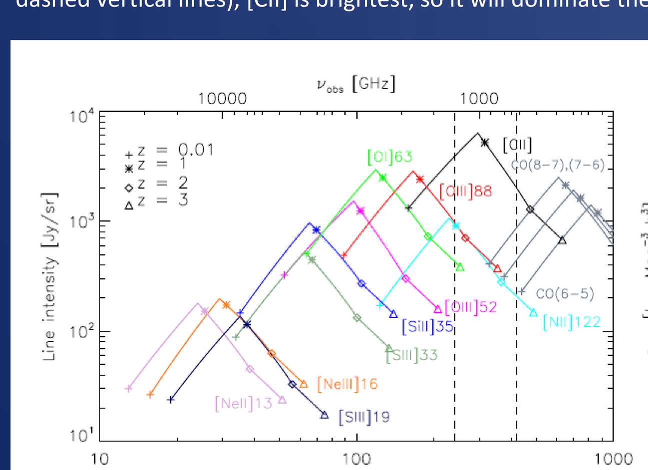


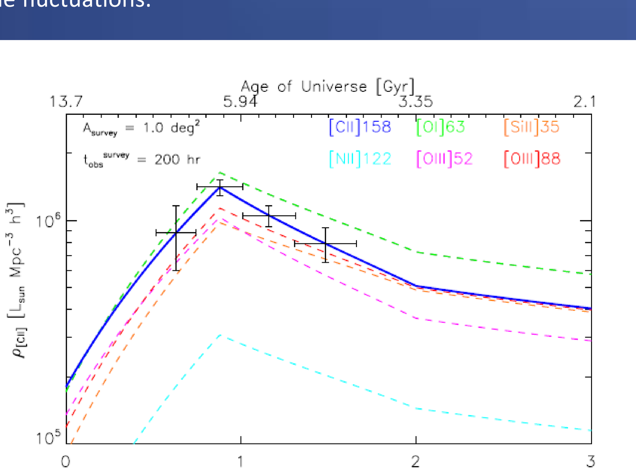


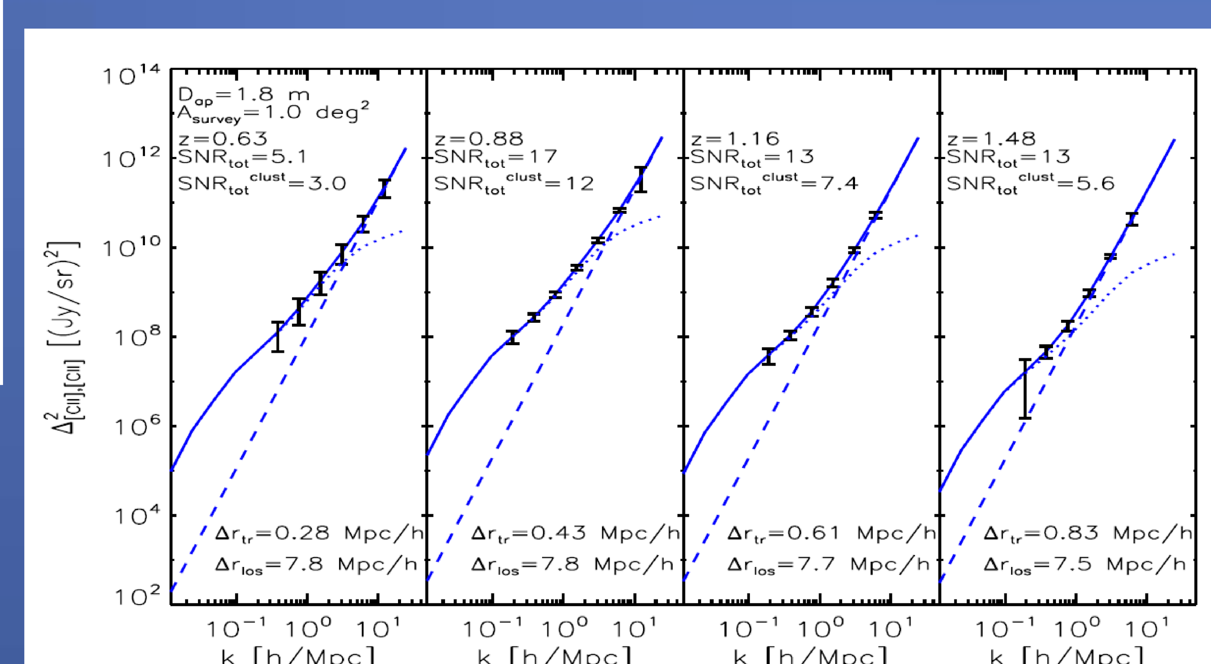
Left: The cosmic extragalactic background light (CMB removed) (Lagache et al 2005) Approximately equal energy emerges in the optical/near-IR and far-IR.

Right: However, as the measurements of far-IR background with Spitzer, Herschel and (shown here) Planck indicate, the far-IR historically dominated the UV energy release through the peak epoch in star-formation activity. Averaged over cosmic time, most of the light from new young stars has been absorbed by dust and re-radiated. With STARFIRE, we will use [CII] to probe this dust-obscured activity from z=1.65 to z=0.52, some 4.5 billion years of cosmic history.

Left: Mean cosmic line intensities of far-IR fine-structure lines based on scaling local-Universe galaxy spectra (Spinoglio et al., 2012) to models of evolving luminosity functions (Bethermin et al. 2011). In the STARFIRE waveband (between dashed vertical lines), [CII] is brightest, so it will dominate the fluctuations.







Predicted auto-correlation power spectra for the [CII] line at four redshifts. Dotted lines show the sum of the 1- and 2-halo clustering terms, and the dashed lines show the "shot noise" or Poisson term due to the discrete nature of galaxies. Error bars are for a 1-square-degree field and 200 hours of integration with a future off-axis LDB program STARFIRE-II. Note that in many of the accessible bins, the clustering raises the amplitude of the power spectrum substantially above the shot noise expectation. Sensitivities at the lowest *k* bins include a strict removal of all instruments modes with mode number ≤ 2 in the spectral dimension and ≤ 1 in the spatial dimensions, as we expect will be required for continuum subtraction and atmospheric removal.

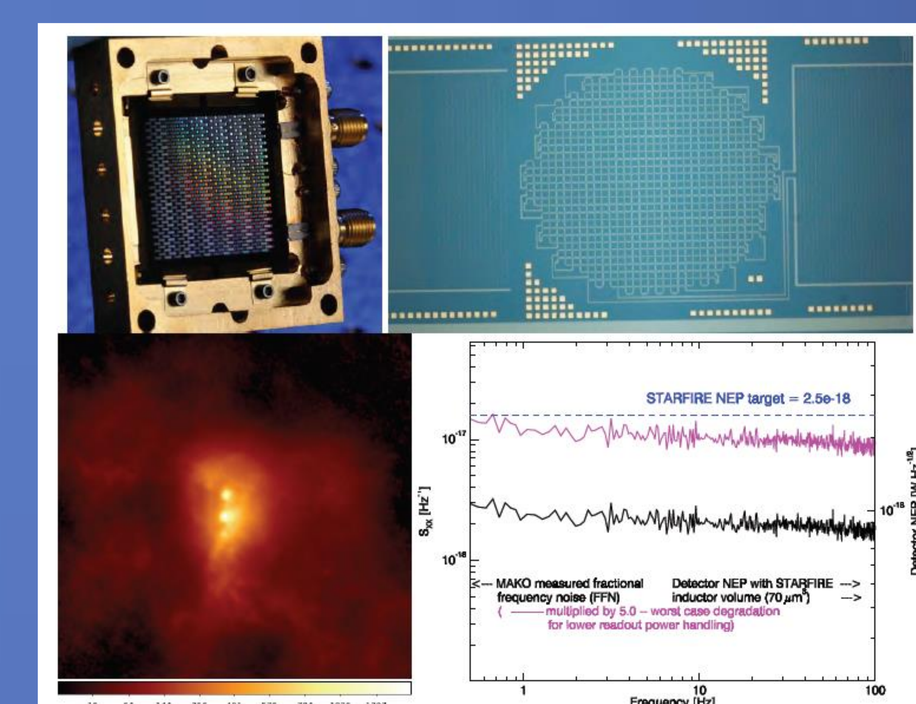
Right: Mean intensities can be extracted from the linear (halo-halo) clustering power in the autocorrelation spectrum. Since redshift is automatically encoded, the mean intensity at each redshift is easily converted to a luminosity density, thus we can chart the history of total [CII] emission. The four error bars show the estimated uncertainties in the [CII] luminosity density obtained via this technique in the 200-hour, 1-degree LDB survey described in the autocorrelation power spectra shown at right. The other lines are shown for completeness as they do not lie in our band. They may be studied with future stratospheric or space missions.

Instrument

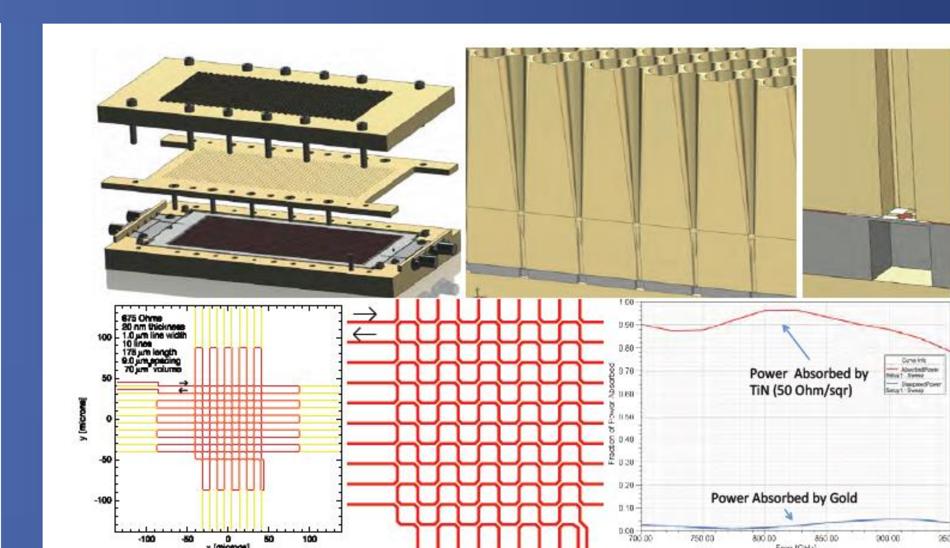
Table 1: STARFIRE Instrument Parameters

Telescope					
Diameter	1.8 m				
Illumination	0.93 (primary mirror is pupil stopped)				
Temperature, Emissivity	270 K, 0.04 (measured on BLAST)				
Detectors					
TiN T_c and base temperature	1.5 K, 250 mK				
KID resonant frequencies, Q	100–250 MHz, 10^5				
STARFIRE pixel response	1.6×10^9 $(\delta f/f)$ W^{-1}, scaled from MAKO as $(\text{volume})^{-1}$				
S_{xx}(due to TLS, Amp)	1.0×10^{-17} $(\delta f/f)^2$ Hz^{-1}, worst case, 5× MAKO				
Detector NEP (optical)	target: 2.5×10^{-18} $W/\sqrt{Hz}$, acceptable 1×10^{-17} $W/\sqrt{Hz}$				
$P_{absorbed}$	27 fW (min), 40 fW (median)				
Photon NEP	1.1×10^{-17} $W/\sqrt{Hz}$ (min), 1.5×10^{-17} $W/\sqrt{Hz}$ (median)				
Spectrometer					
Format	2 modules, each 25 spatial × 64 spectral				
R	450 (670 km s^{-1})				
Optical efficiency	25%, to point source, including horn coupling				
	Short Wavelength		Long Wavelength		
Wavelength range	240 – 276	276 – 317	317 – 365	365 – 420	µm
$\Delta\nu$	2.58	2.25	1.95	1.70	GHz
Beam FWHM	32	37	43	49	"
NEI (median)	6.3	4.6	3.5	2.6	$\times 10^7$ Jy $sr^{-1}\sqrt{sec}$
Line sensitivity (median)	4.6	4.0	3.5	3.1	$\times 10^{-17}$ W $m^{-2}\sqrt{sec}$

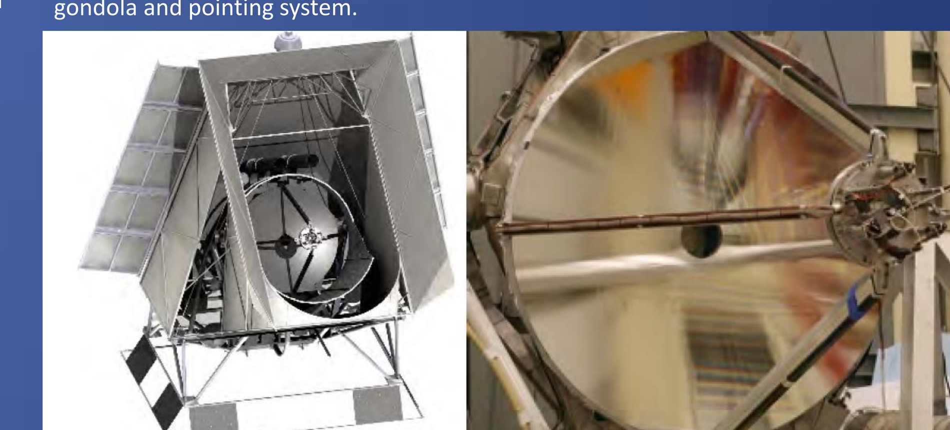
Below: STARFIRE horn-coupled focal-plane array concept. Simple conical horns are drilled in the metal substrate with a custom tool. Alignment between the horn plate, waveguide interface, and base are via alignment pins and this metallic structure is aligned to the silicon with a pin and a pin-and-slot, accommodating the differential CTE. The lithographically patterned KID array includes capacitors patterned alongside the absorbers, and the metal waveguide plate above them is recessed to avoid impacting the KID Q (not shown). The square waveguide couples both polarizations to a single meandered cross-shaped TiN absorber (red trace), with integral back short formed in the wafer via a deep trench etch to a buried oxide layer. The film thickness and the meander shape are tuned to simultaneously provide optimal absorption in the cavity, create the necessary inductance to keep the readout frequencies down, and not exceed the 70 μm^3 volume required to enable the NEP. The various meander sections in the central part of the cross are abutted at the corners so that the capacitance shorts them together at 800 GHz but not at 100 MHz. Gold extensions allow current to flow across the full waveguide width (bottom center). HFSS simulations indicate that with a single step in the waveguide width near the detector (not shown) this absorber provides greater than 90% efficiency across one of the STARFIRE bands.



Single-layer TiN KID array architecture demonstrated on the sky. Top, left shows a 432-pixel KID array (die is 22.5 mm on a side) for the MAKO 350- µm ground-based camera. Top, right shows the pixel detail. A single TiN layer forms the both the meandered inductors, one of which is shown, and the interdigitated capacitors (ends of which are shown alongside the inductor). This pictured device has hexagonal packing (shown schematically in black) with a per-pixel area of 1 mm2 (1.07 mm short hex spacing), and is tuned for MAKO loading. STARFIRE will use a similar design with a slightly larger total pixel area (1.36 mm short hex spacing) but smaller cross-shaped inductor fed by rectangular waveguide, instead of the pictured 350 µm diameter circle). This array has demonstrated photon-noise limited performance and provides the noise and response from which we design the STARFIRE KIDs. This scaling is shown in the plot at lower right: the left hand axis is the measured fractional frequency noise, the right-hand axis shows the NEP which will be obtained with the smaller inductor for STARFIRE. Lower left shows the image of SGR B2 obtained with the 432-pixel MAKO camera at the Caltech Submillimeter Observatory (CSO), demonstrating the system-level maturity of this technology.



STARFIRE telescope and gondola. We will re-use the existing 1.8-meter BLAST telescope, including the secondary focusing mechanism, and copy the existing BLAST gondola and pointing system.



Right: STARFIRE optical design. Two spectrometer modules and an imaging module are all fed with a common Offner-style relay that provides a cold chopping pupil mirror. The full package is sized for the SuperBLASTpol cryostat. The footprint and spot diagram below show the image in the long wavelength module, spanning the full 42' field, and the full δλ/λ = 0.14 instantaneous spectral range, with the grating set to access the long wavelength end of the band (λ = 365 - 420 µm). The Strehl ratio is 0.90 averaged over the array.